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ULTRAFAST PHASE MODULATORS AND SEMICONDUCTOR LASER DEVICES AT 1.3UM

University of Arizona

N. Peyghambarian

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APPROVED:

MARK F. KROL
Project Engineer

FOR THE COMMANDER: Gary D. Barmore

GARY D. BARMORE, Major, USAF
Deputy Director of Surveillance & Photonics

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6. AUTHOR(S)
N. Peyghambarian

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Arizona
2030 E. Speedway
Tucson AZ 85721

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A transmission up-conversion system was built, which consisted of a tunable mode-locked Ti:Sapphire laser and a tunable continuous wave Cr:Forsterite laser. The system has 100 femtosecond time resolution near 1/3um wavelength, limited only by the mode-locked Ti:Sapphire laser pulse width. With the transmission up-conversion system, we observed 5 picosecond carrier capture time in GaInAlAs (11nm)/InAlAs multiple quantum wells (MQWs) at 77K. The continuous wave Cr:Forsterite laser was also used to measure the phase modulation by a current. The maximum 5π phase shift was observed through the 200um long InGaAs/InAlAs MQW laser diode.

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Abstract

A transmission up-conversion system was built which consisted of a tunable mode-locked Ti:Sapphire laser and a tunable continuous wave Cr:Forsterite laser. The system has 100 femtosecond time resolution near 1.3-μm wavelength, only limited by the mode-locked Ti:Sapphire laser pulse width. With the transmission up-conversion system, we observed 5 picosecond carrier capture time in GaInAlAs(11 nm)/InAlAs multiple quantum wells (MQWs) at 77 K. The continuous wave Cr:Forsterite laser was also used to measure the phase modulation by a current. The maximum 5π phase shift was observed through the 200-μm long InGaAs/InAlAs MQW laser diode.

Introduction

The development of optical hardware for near infrared communication systems is evolving rapidly. Semiconductors are far more advantageous than transparent nonlinear media such as $LiNbO_3$, optical fibers, etc. in view of integrated photonics. High refractive indices of semiconductors make device size small, and the state-of-the-art crystal growth technology makes it possible to tailor the bandedge of devices. Also, a semiconductor can be inverted by injecting a current, becoming a gain medium. Not only the intensity of an optical pulse, but also the phase of it, can be modulated by an electric bias while it propagates through semiconductor waveguides. We had proposed to fabricate and test all-optical and optoelectronic semiconductor devices operating near 1.3 μm.

Even though all of the devices we had in mind could not be demonstrated under the circumstances we had, we successfully built a transmission up-conversion system which allowed us to study the carrier dynamics near 1.3 μm with a subpicosecond time resolution. The carrier capture time is a required time for injected carriers to relax to the bottom of bandedge. To develop an efficient and fast light source, the carrier capture time of a certain material and a certain structure is critical, because it determines an efficiency of current injection. When the quantum well width becomes comparable to the free scattering length of carriers, it highly depends on the quantum well structures like well and barrier widths and quantum well depth. With the developed system, we studied the carrier capture time in GaInAlAs/InAlAs MQWs with 11-nm well width. To simulate an electrical carrier injection, we generated carriers optically above the MQW barriers, monitoring a probe transmission at the heavy hole exciton peak. The time-resolved probe transmission showed 5 picosecond carrier capture time with the instantaneous Coulomb screening effect at 77 K. At room temperature, we could not resolve the Coulomb screening effect from the probe transmission increase by the carrier capture.

A semiconductor optical hardware processing optical signals can be made using an intensity modulation through a quantum confined Stark effect. But a phase modulator is more advantageous than an intensity modulator for photonic integrated circuits (PICs) because it allows the manipulation of a spatial intensity distribution, and because it can behave as an intensity modulator if it is arranged to have an interference. The phase of optical pulses can be changed by changing the index of refraction of a waveguide optically or electrically. The optical nonlinearity of an inverted semiconductor has particular interests for PICs application. An inverted semiconductor can provide a gain to weak signal pulses. Also, the optical nonlinearity at the transparency point of an inverted semiconductor has a subpicosecond recovery time even though it is a resonant nonlinearity. The magnitude of optical nonlinearity at the transparency point is so large that an energy deposition due to higher order absorption processes of a strong control pulse is negligible. As proposed, we demonstrated an electrically controlled phase modulation using a separate confinement heterostructure laser diode which consisted of six layers of 4.2-nm $In_{0.53}Ga_{0.47}As$ quantum wells with seven layers of 3.0-nm $In_{0.52}Al_{0.48}As$ barriers. We observed 5π phase change at 1320 nm through the 200-μm-long laser diode by increasing an injected current.

Technical Report

During the term of this project we have developed measurement systems for characterization, as well as design and fabrication skills, useful in the development of optoelectronic semiconductor devices for the 1.3-μm communication wavelength. In particular, we have dealt with phase modulators made of InGaAs/InAlAs and InGaAlAs/InAlAs MQWs and have obtained results for a current-controlled phase modulator with phase shift of up to 5π.

Design considerations

The first parameter in the design of the devices is the operating wavelength. The desired position of the exciton absorption peak is determined by the operating wavelength. For wavelengths near the 1.3-μm region, the well material examined was either the ternary InGaAs or the quaternary InGaAlAs, both lattice-matched to InP. For a given temperature, the well width will determine the exciton position in the ternary system, while more freedom is available in the quaternary system, since the Ga/Al ratio can also be varied. The quaternary system will usually show faster lifetimes. Carrier capture might be another issue to consider. The well widths for the desired exciton position are determined with the use of a program.

The next consideration is light waveguiding. Guiding layers are needed above and below the MQW region to provide vertical confinement. A weighted refractive index is used for the MQW region, which requires a higher refractive index than the cladding layers' refractive indices. Other layers may be needed, such as a buffer layer and a contact layer for the active devices. Single-mode operation in the vertical direction is desired and checked with a slab waveguide program. The thickness of the MQW region, i.e., the number of periods of the well/barrier structure, will depend not only on the optical confinement factor (Γ), but also on issues such as uniformity of the carrier distribution on the wells, carrier concentration needed to achieve the desired performance, and current budget for the active devices. In the transverse direction, light is confined by etching a rib and, therefore, creating a transverse step in the refractive index. This can be roughly calculated by using the effective index approach, which also allows checking the confinement in the transverse direction. For the required phase shift per unit length of the device, given the rib width, a range for the etching depth can be found to maintain good guiding properties, despite the changes in the refractive index occurring during the operation of the device.

Sample fabrication

The sample processing includes the following steps: (1) cleaving the sample into processable sizes; (2) photolithographic patterning with photoresist, mask, and UV lamp; (3) etching of the rib, usually done on a reactive ion etching machine with BCl_3; (4) polishing to remove substrate and improve the thermal properties; (5) for the active devices, metal coating and annealing to obtain ohmic contacts; (6) further cleaving into device usable sizes; and (7) for the case of active devices, indium contact mounting on a heatsink.

Cr:Forsterite laser

We built a continuous wave chromium doped forsterite (Cr:Forsterite) laser which is tunable between 1220 nm and 1330 nm, with an average power of over 500 mW at the gain peak. This solid state laser is pumped by a mode-locked 1064-nm Nd:YAG, which can deliver over 10 W of average power.

A schematic of the Cr:Forsterite laser is shown in Fig. 1, where the layout is that of a typical Z cavity with a Brewster cut crystal and astigmatism compensation. Due to the poor thermal properties of the crystal, this is wrapped with indium foil and mounted with a TE cooler on a water-cooled brass mount. A temperature controller keeps the temperature close to the dew point, maximizing the performance of the laser. The laser mirrors are wide-band and centered at 1250 nm, and the wavelength of the laser is tuned using a birefringent plate at Brewster's angle.

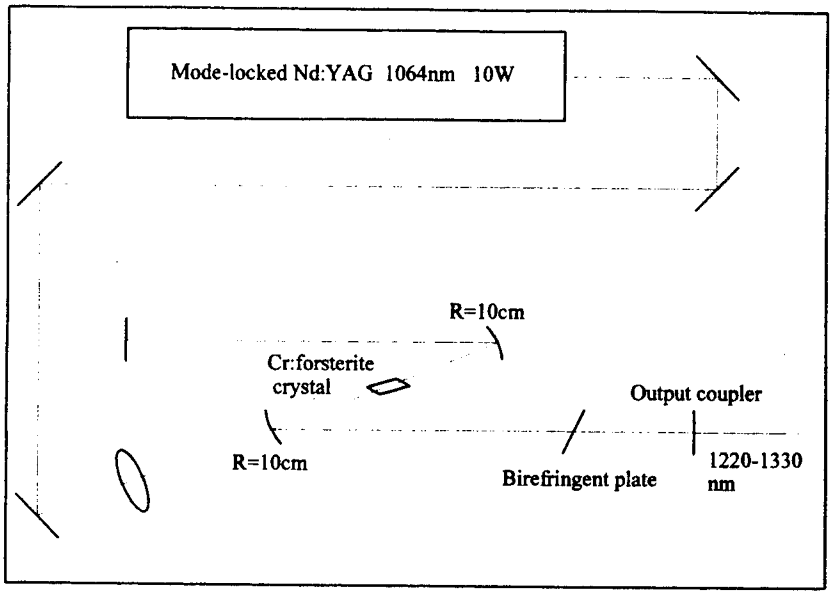

Figure 1. Cr:Forsterite laser.

Transmission upconversion system

A time-resolved transmission measurement system was developed to measure changes in the optical absorption for the materials used near the 1.3-μm wavelength region. In this system, an upconversion technique is used with the Cr:Forsterite laser described above and a self-mode-locked Ti:sapphire laser. The Ti:sapphire laser produces 100-fs pulses at a repetition rate of 80 MHz with several hundred mW of average power, and is tunable between 790 nm and 910 nm.

The schematic of the upconversion system is shown in Fig. 2. The sample was excited by the Ti:sapphire pump pulses, and the cw Cr:Forsterite was used as a tunable probe. The probe was then upconverted with the reference Ti:sapphire 100-fs pulses on a nonlinear crystal, and the resulting signal was spectrally filtered and lock-in detected, yielding a direct measurement of the change in absorption due to the pump with 100-fs temporal resolution.

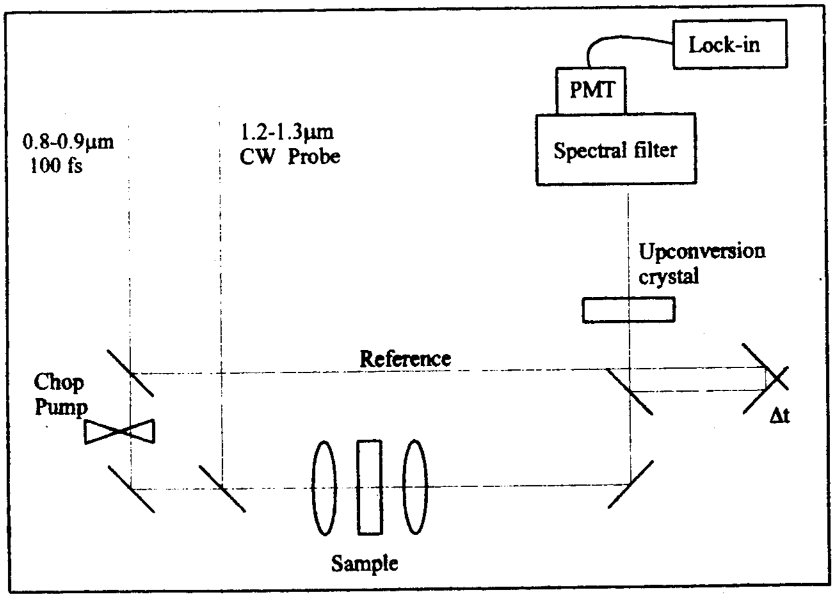

Figure 2. Time-resolved transmission system using a cw/femtosecond upconversion technique.

<u>Carrier capture time measurements</u>

One type of measurement performed with the time-resolved transmission measurement system was the determination of the capture time of carriers in the wells for several MQW samples.

Figure 3 shows relative differential transmission curves of the probe for different pump irradiances. This particular sample was a GaInAlAs/InAlAs MQW lattice-matched to InP with well widths of 11 nm. The peak of the heavy-hole exciton at 77 K was at 1285 nm, and the cw probe was tuned to this wavelength. The pump wavelength was at 787 nm, generating carriers in the continuum. The transmission curves show two time constants, one that follows the pump pulse and a longer one of approximately 5 ps. The first time constant comes from the exciton screening due to the Coulomb interaction with the generated carriers, and the longer one is due to the carrier cooling, giving the carrier capture time by the wells. For room-temperature measurements, the samples typically showed only one time constant.

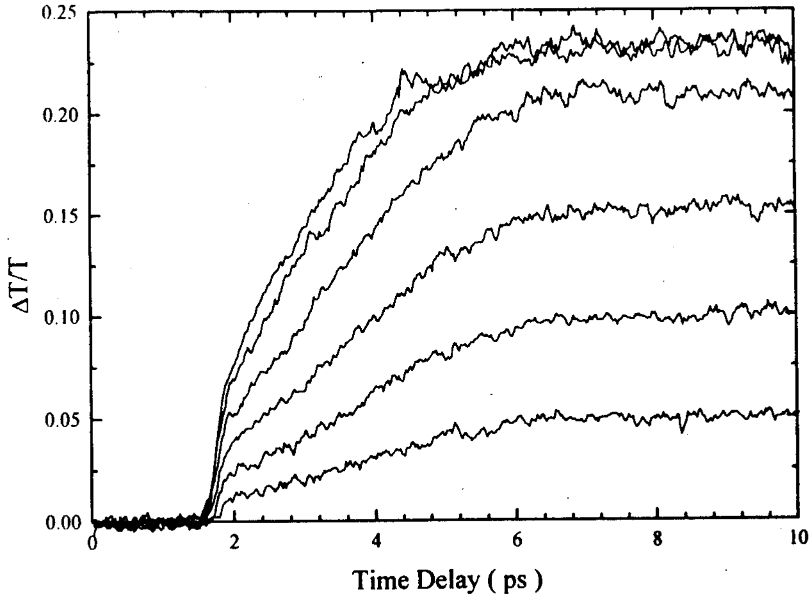

Figure 3. Differential transmission for different pump intensities.

Current-controlled phase shifter

Figure 4 depicts the structure of the phase shifter that was used. It consists of six layers of 4.2-nm $In_{0.53}Ga_{0.47}As$ quantum wells, with seven layers of 3.0-nm $In_{0.52}Al_{0.48}As$ barriers. These are lattice-matched to the InP substrate. The two layers of $In_{0.78}Ga_{0.22}As_{0.55}P_{0.45}$ above and below the MQW active region are the guiding layers used to confine the light in the vertical direction. The sample has 80-μm-wide strips of InP separated by 300 μm, and is approximately 200-μm long. It is soldered to a silicon heatsink on a copper mount and further mounted on a copper/brass finger, temperature controlled by a TE cooler as well as water cooled.

p-doped $1x10^{19}$ cm^{-3}	$Ga_{0.47}In_{0.53}As$	0.1µm	
p-doped $1x10^{18}$ cm^{-3}	InP	2µm	
p-doped $5x10^{17}$ cm^{-3}	$In_{0.78}Ga_{0.22}As_{0.55}P_{0.45}$		0.6µm
	$Ga_{0.47}In_{0.53}As$	42A	6x
	$Al_{0.48}In_{0.52}As$	30A	
n-doped $5x10^{17}$ cm^{-3}	$In_{0.78}Ga_{0.22}As_{0.55}P_{0.45}$		
n-doped $1x10^{18}$ cm^{-3}	InP	1µm	
n-doped	InP	substrate	

Figure 4. Structure of MQW 627 A.

A schematic of the set-up used to determine the phase shift with current is shown in Fig. 5. The probe laser is the cw Cr:Forsterite laser described above. Light was coupled into the waveguide using a 40x diode-laser lens and collected with a 20x diode-laser lens. The output light was focused on an InGaAs photodiode connected to a digitizing oscilloscope. Part of the light was deflected with a beam splitter so that the end facet of the sample was imaged onto an Electrophysics 7290 camera, which is connected to a monitor to assist in the alignment. The spectral data was taken with a Spexmono model 270M scanning spectrometer.

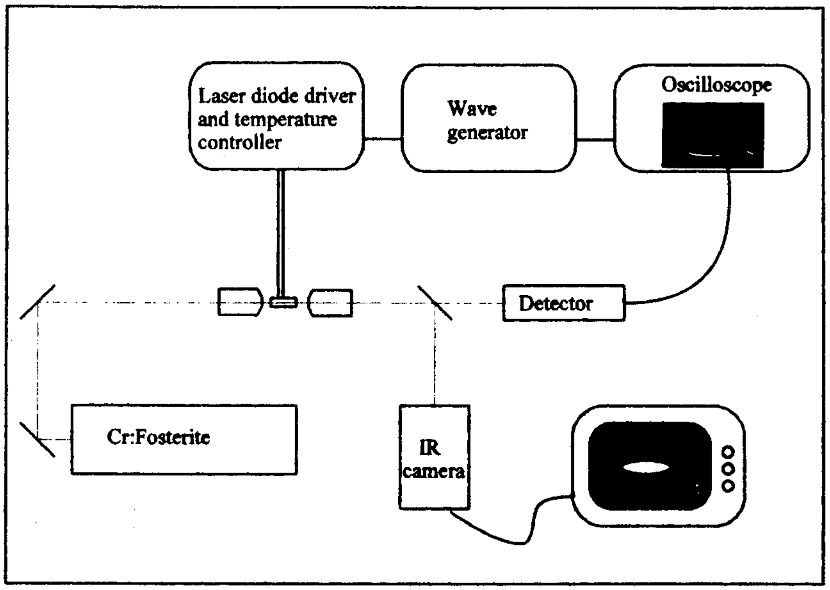

Figure 5. Phase shift set-up.

Sawtooth current pulses of several peak values were applied to the sample. As the current increases, the change in the refractive index changes the effective length of the sample, as seen by the cw probe laser. The sample acts as a Fabry-Perot, where the mirrors are the facets, and the cw probe laser sees the peaks and troughs of the Fabry-Perot transmission as the Fabry-Perot length is changed. This is seen on the output intensity curve shown on the oscilloscope, where the amount of phase shift can be directly obtained by counting the number of peaks transversed by the probe. Figure 6 shows a typical picture from the oscilloscope. Figure 7 shows the difference between the electroluminescence and the probe with leakage, where 5 peaks can be observed. The peak current density is $3125 A/cm^2$, and the calculated confinement factor (Γ) is 4.5%. Figure 8 shows the spectrum for the same conditions as the previous curves. At the wavelength shown, the probe is in the gain region of the sample, and when the sample was heated, deeper fringes were observed as the gain region shifts to longer wavelengths.

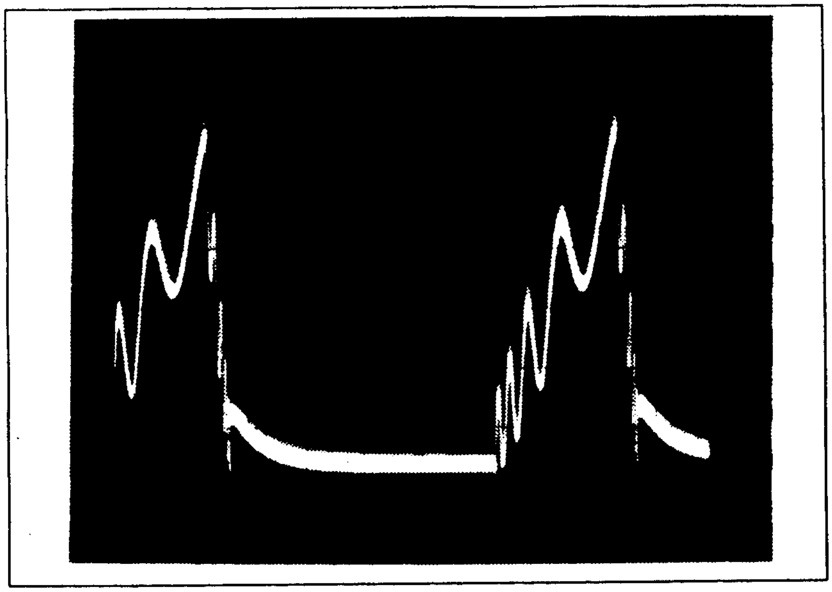

Figure 6. Typical oscilloscope output waveform.

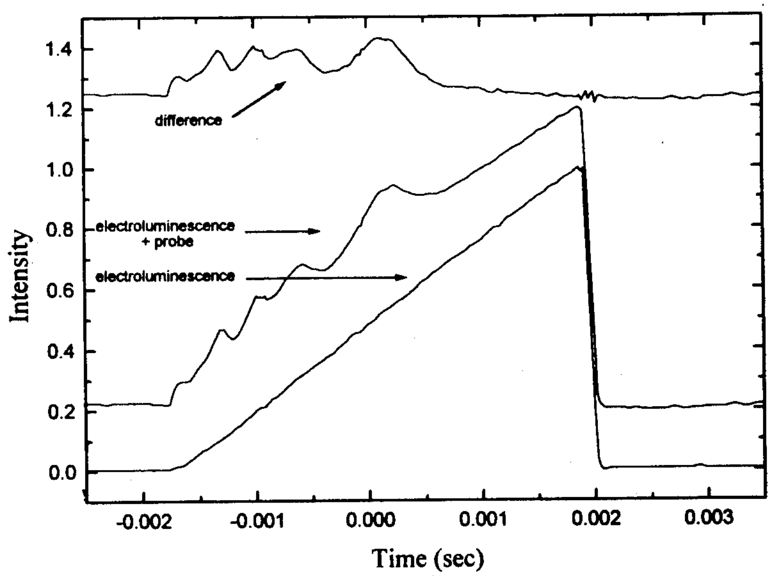

Figure 7. Output intensity for MQW 627 A.

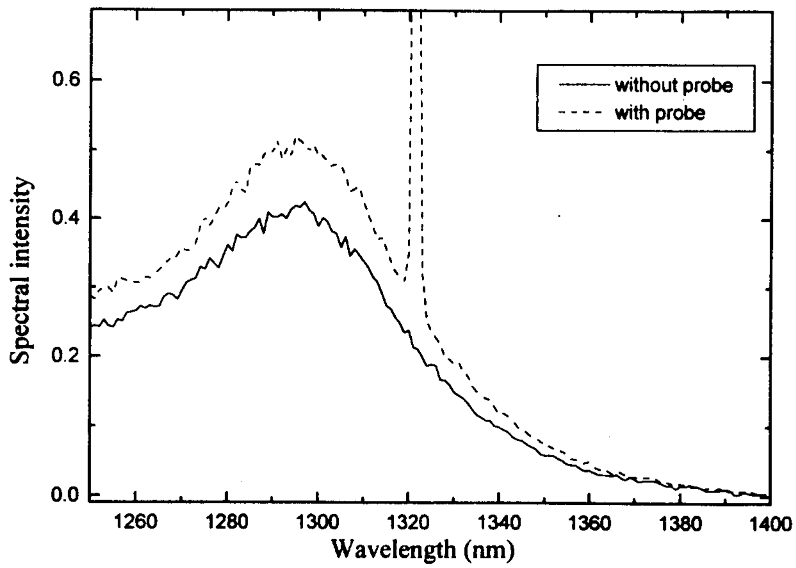

Figure 8. Spectrum of output intensity for MQW 627 A.

Summary

In this project we built a transmission up-conversion system which consisted of a tunable mode-locked Ti:Sapphire laser and a tunable continuous wave Cr:Forsterite laser. The tuning range of the Ti:Sapphire laser was from 790-910 nm, and the continuous wave Cr:Forsterite laser was tunable from 1220-1330 nm. The transmission up-conversion system has 100 femtosecond time resolution near 1.3-μm wavelength, only limited by the mode-locked Ti:Sapphire laser pulse width. Using the system we observed 5 picosecond carrier capture time in GaInAlAs(11 nm)/InAlAs MQWs at 77 K with the instantaneous Coulomb screening effect. The continuous wave Cr:Forsterite laser was also used to measure the phase modulation by a current. The maximum 5π phase shift was observed through the 200-μm-long InGaAs/InAlAs MQW laser diode. This information on the carrier capture time and the phase shift are critical parameters to develop unit devices such as a high-speed laser diodes and an ultrafast all-optical switching device for inverted semiconductor PICs which can be deployed directly to the current optical fiber communication network.

Publications

M. F. Krol, S. Ten, B. P. McGinnis, M. J. Hayduk, G. Khitrova, and N. Peyghambarian, "Ultrafast hole tunneling by nonresonant delocalization in asymmetric double quantum wells," Phys. Rev. B **52** (20), 1995.

M. F. Krol, R. K. Boncek, M. J. Hayduk, S. Ten, T. Ohtsuki, B. P. McGinnis, G. Khitrova, H. M. Gibbs, and N. Peyghambarian, "Novel multiple quantum well modulators for optical interconnects," European Symposium on *Advanced Networks and Services*, Amsterdam, The Netherlands, March 20-24, 1995.

M. Krol, S. Ten, B. P. McGinnis, M. J. Hayduk, G. Khitrova, and N. Peyghambarian, "Ultrafast hole tunneling in asymmetric double quantum wells," SPIE Conference on *Optoelectronic Integrated Circuits, Materials, Physics, and Devices*, San Jose, California, Feb. 4-10, 1995.

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